

Anomalous $WW\gamma$ Vertex at LC+HERA Based γp Collider

S. Ata \ddot{g} and $\dot{I}.T.$ Çakir

Ankara University Department of Physics

Faculty of Sciences, 06100 Tandoğan, Ankara, Turkey

The potential of LC+HERA based γp collider to probe $WW\gamma$ vertex is presented through the discussion of sensitivity to anomalous couplings and p_T distribution of the final quark. The limits of $-0.16 < \Delta\kappa < 0.14$, $-0.30 < \lambda < 0.30$, at 95% C.L. can be reached with integrated luminosity $100 pb^{-1}$ and they are competitive to projected future limits from other colliders. The results are compared with corresponding ep collider using Weizsäcker-Williams Approximation.

I. INTRODUCTION

Recently there have been intensive studies to test the deviations from the Standard Model (SM) at present and future colliders. The investigation of three gauge boson couplings plays an important role to manifest the non abelian gauge symmetry in standard electroweak theory. The precision measurement of the triple vector boson vertices will be the crucial test of the structure of the SM.

Analysis of $WW\gamma$ vertex has been given by several papers for Fermilab [1], LEP2 [2] and ep [3–8] collider DESY HERA. One of further projects is the Linear Collider (LC) design at DESY [9] which is the only one that can be converted into an ep [10,11] collider. An additional advantage of the linac-ring type ep colliders is the possibility of building γp colliders on their bases [12]. The high energy gamma beam is obtained by the Compton backscattering of laser photons off linac’s electron beam. Estimations show that this possibility appears quite realistic, since the spectrum of the scattered laser photons is hard and the luminosity for γp turns out to be of the same order as the one for ep collision. According to present project at DESY 500 GeV electrons are allowed to collide 820 GeV protons [10,11]. In this case the corresponding parameters of the γp collider are shown in Table I [12]. For photo-production processes the cross sections in γp machines are about one order of magnitude larger than corresponding ep machines. Therefore such kind of high energy γp colliders will be complementary tools to linac ring type ep colliders.

In this paper we examine the potential of future LC+HERA based γp collider to probe anomalous $WW\gamma$ coupling and compare the results from ep collider.

TABLE I. Main parameters of LC+HERA based γp collider.

Machine	$\sqrt{s_{ep}}$ TeV	$\sqrt{s_{\gamma p}}$ TeV	$L_{\gamma p}(cm^{-1}s^{-1})$
LC+HERA	1.28	1.16	2.5×10^{31}

II. LAGRANGIAN AND CROSS SECTIONS

C and P parity conserving effective lagrangian for two charged and one photon interaction can be written following the papers [13,14]

$$L = e(W_{\mu\nu}^\dagger W^\mu A^\nu - W^{\mu\nu} W_\mu^\dagger A_\nu + \kappa W_\mu^\dagger W_\nu A^{\mu\nu} + \frac{\lambda}{M_W^2} W_{\rho\mu}^\dagger W_\nu^\mu A^{\mu\rho}) \quad (1)$$

where

$$W_{\mu\nu} = \partial_\mu W_\nu - \partial_\nu W_\mu$$

and dimensionless parameters κ and λ are related to the magnetic and electric dipole moments. $\kappa = 1$ and $\lambda = 0$ correspond Standard Model values. In momentum space this has the following form with momenta $W^+(p_1), W^-(p_2)$ and $A(p_3)$

$$\begin{aligned} \Gamma_{\mu\nu\rho}(p_1, p_2, p_3) = & e[g_{\mu\nu}(p_1 - p_2 - \frac{\lambda}{M_W^2}[(p_2.p_3)p_1 - (p_1.p_3)p_2])_\rho \\ & + g_{\mu\rho}(\kappa p_3 - p_1 + \frac{\lambda}{M_W^2}[(p_2.p_3)p_1 - (p_1.p_2)p_3])_\nu \\ & + g_{\nu\rho}(p_2 - \kappa p_3 - \frac{\lambda}{M_W^2}[(p_1.p_3)p_2 - (p_1.p_2)p_3])_\mu \\ & + \frac{\lambda}{M_W^2}(p_{2\mu}p_{3\nu}p_{1\rho} - p_{3\mu}p_{1\nu}p_{2\rho})] \end{aligned} \quad (2)$$

where $p_1 + p_2 + p_3 = 0$.

There are three Feynman diagrams for the subprocess $\gamma q_i \rightarrow W q_j$ and only t-channel W exchange graph contributes $WW\gamma$ vertex. Therefore γp collision isolates $WW\gamma$ coupling but corresponding ep process has the mixtures of $WW\gamma$ and WWZ couplings.

The unpolarized differential cross section for the subprocess $\gamma q_i \rightarrow W q_j$ can be obtained using helicity amplitudes from [6] summing over the helicities

$$\frac{d\hat{\sigma}}{d\hat{t}} = \frac{2}{\hat{s} - M_W^2} \frac{\beta}{64\pi\hat{s}} \sum_{\lambda_\gamma \lambda_W} \frac{1}{2} M_{\lambda_\gamma \lambda_W}^2 \quad (3)$$

where

$$M_{\lambda_\gamma \lambda_W} = \frac{e^2}{\sqrt{2} \sin \theta_W} \frac{\hat{s}}{\hat{s} + M_W^2} \sqrt{\beta} A_{\lambda_\gamma \lambda_W}, \quad \beta = 1 - \frac{M_W^2}{\hat{s}} \quad (4)$$

and θ_W is the Weinberg angle.

For the signal we are considering a quark jet and on-shell W with leptonic decay mode

$$\gamma p \rightarrow W + \text{jet} \rightarrow \mu + p_T^{\text{miss}} + \text{jet} \quad (5)$$

In this mode charged lepton and the quark jet are in general well separated and the signal is in principle free of background of SM.

The total cross section for the subprocess $\gamma q_i \rightarrow W q_j$ can be obtained as follows [5]:

$$\begin{aligned} \hat{\sigma} = & \frac{\alpha G_F M_W^2}{\sqrt{2}\hat{s}} |V_{q_i q_j}|^2 \{ (|e_q| - 1)^2 (1 - 2\hat{z} + 2\hat{z}^2) \log(\frac{\hat{s} - M_W^2}{\Lambda^2}) - [(1 - 2\hat{z} + 2\hat{z}^2) \\ & - 2|e_q|(1 + \kappa + 2\hat{z}^2) + \frac{(1 - \kappa)^2}{4\hat{z}} - \frac{(1 + \kappa)^2}{4}] \log \hat{z} + [(2\kappa + \frac{(1 - \kappa)^2}{16}) \frac{1}{\hat{z}} \\ & + (\frac{1}{2} + \frac{3(1 + |e_q|^2)}{2})\hat{z} + (1 + \kappa)|e_q| - \frac{(1 - \kappa)^2}{16} + \frac{|e_q|^2}{2}](1 - \hat{z}) \\ & - \frac{\lambda^2}{4\hat{z}^2}(\hat{z}^2 - 2\hat{z} \log \hat{z} - 1) + \frac{\lambda}{16\hat{z}}(2\kappa + \lambda - 2)[(\hat{z} - 1)(\hat{z} - 9) + 4(\hat{z} + 1) \log \hat{z}]\} \end{aligned} \quad (6)$$

where $\hat{z} = M_W^2/\hat{s}$ and Λ^2 is cut off scale in order to regularize \hat{t} -pole of the colinear singularity for massles quarks. In the case of massive quarks there is no need such a kind of cut. To get numerical results we take into account the integrated cross section over quark distributions inside the proton and the spectrum of the backscattered laser photons [12].

$$\sigma = \int_{\tau_{min}}^{0.83} d\tau \int_{\tau/0.83}^1 \frac{dx}{x} f_{\gamma/e}(\tau/x) f_{q/p}(x, Q^2) \hat{\sigma}(\tau s) \quad (7)$$

with $\tau_{min} = (M_W + M_q)^2/s$

In Table II integrated total cross sections times branching ratio of $W \rightarrow \mu\nu$ and corresponding number of events per year are shown for various values of κ and λ . Number of events has been calculated using

$$N = \sigma(\gamma p \rightarrow W + Jet) B(W \rightarrow \mu\nu) A L_{int} \quad (8)$$

where we take the acceptance in the muon channel A and integrated luminosity L_{int} as 65% and 100pb^{-1} . To give an idea about the comparison with corresponding ep collider the cross sections obtained using Weizsäcker-Williams approximation are also shown on the same table. Through the calculations proton structure functions of Martin, Robert and Stirling (MRS A) [15] have been used with $Q^2 = M_W^2$. As the cross section $\sigma(\gamma p \rightarrow W + Jet)$ we have considered the sum of $\sigma(\gamma u \rightarrow W^+ d)$, $\sigma(\gamma \bar{d} \rightarrow W^+ \bar{u})$, $\sigma(\gamma \bar{s} \rightarrow W^+ \bar{c})$, $\sigma(\gamma u \rightarrow W^+ s)$, $\sigma(\gamma \bar{s} \rightarrow W^+ \bar{u})$, and $\sigma(\gamma \bar{d} \rightarrow W^+ \bar{c})$.

TABLE II. Integrated total cross section times branching ratio $\sigma(\gamma p \rightarrow W j) \times B(W^+ \rightarrow \mu\nu)$ in pb and corresponding number of events(in parentheses) for some κ and λ values.

Backscattered Laser	WWA	κ	λ
13.8(845)	1.3(85)	1	0
25.1(1631)	1.9(123)	1	1
59.0(3835)	3.7(240)	1	2
9.7(631)	0.9(60)	0	0
23.4(1521)	2.1(137)	2	0

As shown from Table II the cross sections using backscattered laser photons are considerably larger than the case of corresponding ep collision. We assume that the form factor structure of $\kappa - 1$ and λ do not depend on the momentum transfers at the energy region considered. Then anomalous terms containing κ grow with $\sqrt{\hat{s}}/M_W$ and terms with λ rise with \hat{s}/M_W^2 . Deviation $\Delta\kappa = \kappa - 1 = 1$ from SM value changes the total cross sections 30-70% whereas the $\Delta\lambda = \lambda = 1$ gives 80% changes. Therefore high energy will improve the sensitivity to anomalous couplings. For comparison with HERA energy $\sqrt{s} = 314$ GeV the similar results would be 20-40% for $\Delta\kappa = 1$ and 5% for $\Delta\lambda = 1$.

It is important to see how the anomalous couplings change the shape of the transverse momentum distributions of the final quark jet. For this reason we use the following formula:

$$\frac{d\sigma}{dp_T} = 2p_T \int_{y^-}^{y^+} dy \int_{x_a^{min}}^{0.83} dx_a f_{\gamma/e}(x_a) f_{q/p}(x_b, Q^2) \left(\frac{x_a x_b s}{x_a s - 2m_T E_p e^y} \right) \frac{d\hat{\sigma}}{d\hat{t}} \quad (9)$$

where

$$y^\mp = \log \left[\frac{0.83s + m_q^2 - M_W^2}{4m_T E_p} \mp \left\{ \left(\frac{0.83s + m_q^2 - M_W^2}{4m_T E_p} \right)^2 - \frac{0.83 E_e}{E_p} \right\}^{1/2} \right] \quad (10)$$

$$\begin{aligned} x_a^{(1)} &= \frac{2m_T E_p e^y - m_q^2 + M_W^2}{s - 2m_T E_e e^{-y}} , \quad x_a^{(2)} = \frac{(M_W + m_q)^2}{s} \\ x_a^{min} &= MAX(x_a^{(1)}, x_a^{(2)}) , \quad x_b = \frac{2m_T E_e x_a e^{-y} - m_q^2 + M_W^2}{x_a s - 2m_T E_p e^y} \end{aligned} \quad (11)$$

with

$$\begin{aligned} \hat{s} &= x_a x_b , \quad \hat{t} = m_q^2 - 2E_e x_a m_T e^{-y} , \quad \hat{u} = m_q^2 + M_W^2 - \hat{s} - \hat{t} \\ m_T^2 &= m_q^2 + p_T^2 \end{aligned} \quad (12)$$

The p_T spectrum $B(W \rightarrow \mu\nu) \times d\sigma/dp_T$ of the quark jet is shown in Fig. 1 for various κ and λ values at LC+HERA based γp collider. Similar distribution is given in Fig. 2 for Weizsäcker-Williams Approximation that covers the major contribution from ep collision. It is clear that the cross section at large p_T is quite sensitive to anomalous $WW\gamma$ couplings. As λ increases the cross section grows more rapidly when compared with κ dependence at high p_T region $p_T > 100$ GeV. The cross sections with real gamma beam are one order of magnitude larger than the case of WWA. Comparison between two figures also shows that the curves become more separable as \hat{s} gets large.

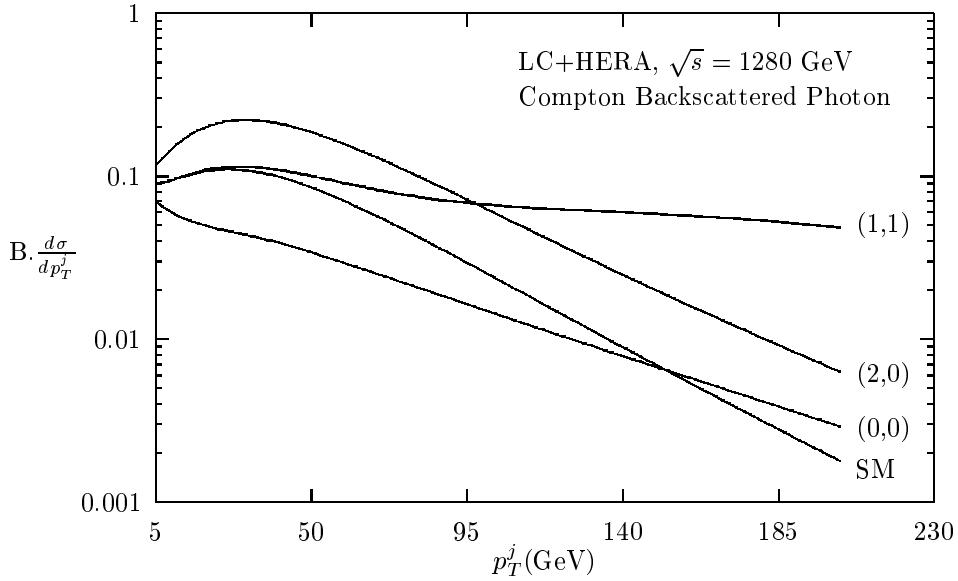


FIG. 1. κ and λ dependence of the transverse momentum distribution of the quark jet at LC+HERA based γp collider (Compton Backscattered Photon). The unit of the vertical axis is pb/GeV and the numbers in the parentheses stand for anomalous coupling parameters (κ, λ) .

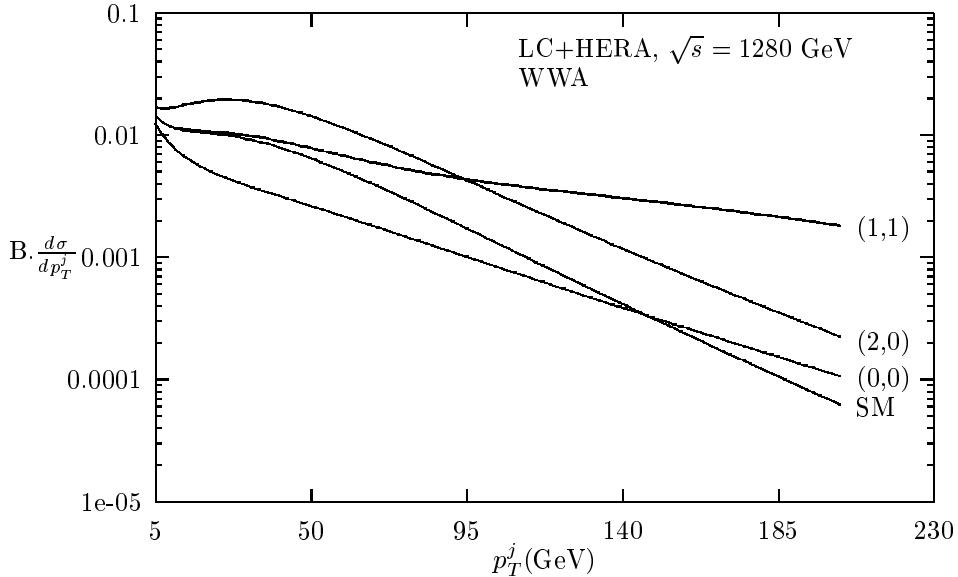


FIG. 2. The same as the Fig.1 but for Weizsäcker Williams Approximation.

III. SENSITIVITY TO ANOMALOUS COUPLINGS

We can estimate sensitivity of LC+HERA based γp collider to anomalous couplings by assuming the uncertainty in the luminosity measurement to be 2% and systematic errors in the acceptance to be 2% for $\mu\nu$ decay channel of the W and for the integrated luminosity values of 10^2 pb^{-1} . The acceptance in the muon channel is taken to be 65%. We use the following expression to add statistical and systematic errors to get the uncertainty on the cross section measurement

$$\frac{\Delta\sigma}{\sigma} = \left(\frac{1}{N} + \left(\frac{\Delta L}{L} \right)^2 + \left(\frac{\Delta A}{A} \right)^2 \right)^{\frac{1}{2}} \quad (13)$$

where N is the number of W^+ and W^- events given with their branching ratios in the $\mu\nu$ channel and A is the acceptance of the related channel. Above formula gives the following limits on the $\Delta\kappa$ and λ for the deviation of the total cross section from the Standard Model value at 68% and 95% confidence levels:

$$\begin{aligned} -0.08 < \Delta\kappa < 0.08, & \quad -0.22 < \lambda < 0.22, \quad 68\% \text{ C.L.} \\ -0.16 < \Delta\kappa < 0.14, & \quad -0.30 < \lambda < 0.30, \quad 95\% \text{ C.L.} \end{aligned}$$

On the ground of comparison we give the limits at ep collider using Weizsäcker-Williams Approximation:

$$\begin{aligned} -0.20 < \Delta\kappa < 0.19, & \quad -0.43 < \lambda < 0.43, \quad 68\% \text{ C.L.} \\ -0.46 < \Delta\kappa < 0.37, & \quad -0.62 < \lambda < 0.62, \quad 95\% \text{ C.L.} \end{aligned}$$

In the Compton backscattered photon case the sensitivity is limited by the systematic errors and comparable to the limits from projected future colliders [8]. However this is limited by the statistics rather than systematic errors for WWA case. Taking into account both the transverse momentum distribution of the quark jet and the sensitivity in the total cross section leads to very promising results for probing $WW\gamma$ vertex at γp collider based on LC+HERA.

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